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The funding for the work reported here was provided by an STTR Phase II AFOSR grant. This report covers the design, fabrication, and test of proof-of-concept miniature electrooptic (EO) modulators at 1550 nm wavelength, based on state-of-the-art hybrid silicon/polymer/sol-gel technology. TIPD, LLC and the University of Arizona have demonstrated, for the first time, miniature hybrid phase modulators that are fabricated on silicon-on-insulator (SOI) substrates utilizing a novel Si nanostrip infrastructure for light guidance and superior EO polymers for signal modulation. The realization of such SOI-based hybrid modulator devices provides a critical leap towards the eventual accomplishment of low-cost, chip-based silicon photonics.

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High-speed, Low Voltage, Miniature Electro-optic Modulators Based on Hybrid Photonic-Crystal/Polymer/Sol-Gel Technology

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February 2012

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GLOSSARY

BOX	buried oxide
CMOS	complementary metal–oxide–semiconductor
EO	electrooptic
ITO	indium tin oxide
PC	photonic crystal
PMMA	poly (methyl methacrylate)
Si	silicon
SOI	silicon-on-insulator
TE	transverse electric
TM	transverse magnetic

1. EXECUTIVE SUMMARY

The funding for the work reported here was provided by an STTR Phase II AFOSR grant. This report covers the design, fabrication, and test of proof-of-concept miniature electrooptic (EO) modulators at 1550 nm wavelength, based on state-of-the-art hybrid silicon/polymer/sol-gel technology. TIPD, LLC and the University of Arizona have demonstrated, for the first time, miniature hybrid phase modulators that are fabricated on silicon-on-insulator (SOI) substrates utilizing a novel Si nanostrip infrastructure for light guidance and superior EO polymers for signal modulation. The realization of such SOI-based hybrid modulator devices provides a critical leap towards the eventual accomplishment of low-cost, chip-based silicon photonics.

2. INTRODUCTION

In the past decade, the intense effort dedicated to developing polymer electrooptic (EO) modulators has been mostly driven by the demand for ultrahigh modulation speed up to a few hundreds of GHz. This ultrafast modulation has wide-spread applications ranging from commercial telecommunications networks to defense applications including photonic generation of RF signals for phased array antennas and remote antennas. Poled EO polymers, with their demonstrated inherently faster response time on the order of femtosecond [1], are ideal candidates to handle ultrafast processes with modulation bandwidth achievable up to 1.6 THz [2]. Therefore, EO polymers have the advantage for all ultrafast modulation applications due to their tremendous performance.

Of particular note, there is a strong and growing demand for accomplishing ultrafast EO modulation directly on silicon (Si) chips. The desire to guide near infrared light in Si waveguides and enable various photonic functions, such as light emission, modulation, and detection, together with passive silicon waveguides and integrated microelectronic on silicon-on-insulator (SOI) substrates, is set to revolutionize the next generation, of multi-functional, photonic/microelectronic Si chips, a capability that currently is only available on expensive platforms like indium phosphide. Among techniques to directly modulate the refractive index of Si, the carrier injection approach has so far been the most successful. Carrier injection, however, is itself not an ultrafast process due to its carrier lifetime limitation. The state-of-the-art of direct Si index modulation is currently at about 20 GHz bandwidth [3]. To substantially increase the bandwidth to > 100 GHz, the carrier lifetime in Si has to be reduced to 10 ps or less, a challenge that has yet to find a solution, since it is practically intrinsic to the nature of silicon itself.

The availability of ultrafast EO polymers with mature processing techniques, coupled with the comprehensive utilization of Si chips in all application areas, inspired us to explore hybrid EO modulators that utilize Si waveguides as the light guiding infrastructure and EO polymers as the active functional material. Efforts to build hybrid Si light-guiding, polymer-modulating, EO modulators based on SOI substrates have investigated a variety of Si structures including single-mode strip waveguides, line-defect photonic crystal (PC) waveguides, and nanoslotted waveguides. Single-mode Si strip waveguides need to be covered by EO polymer cladding in which case the modulation is done via the evanescent tail of the transmitted light that penetrates into the polymer cladding. However, due to the large index contrast between Si (~3.5) and EO polymer (~1.6), the light is tightly confined inside the Si waveguide and typically only 1% or less of the intensity can penetrate into the functional cladding for standard silicon strip dimensions, thus resulting in a very ineffective modulator device. In the line-defect photonic crystal waveguide approach, EO polymer is supposed to infiltrate into the air holes of the photonic crystal structure in order to control the photonic bandgap properties [4]. While this is a fascinating concept, the complexity and delicacy of photonic crystal waveguide fabrication and the subsequent EO polymer infiltration has led to no demonstrated devices to date. Very recently, nanoslotted Si waveguides have been proposed to have functional EO polymers infiltrated into the nanoslots, whose width ranges from a few tens to up to one hundred nanometers. The significantly enhanced transverse electric (TE) mode intensity inside the Si nanoslots [5] can in principle lead to low-voltage, ultrafast, miniature EO modulator devices. However, during the early period of the program, our fabrication efforts led to the conclusion that the Si nanoslot approach suffered from several severe difficulties, including very high mode conversion loss between a standard Gaussian-shaped strip waveguide mode and the central-lobe-enhanced nanoslotted waveguide mode, as well as the formidable task of electrode deposition on the nanoslotted walls. So far, the only published polymer-filled Si nanoslotted waveguide based modulator has > 40dB transmission loss [6].

Therefore, in this Phase II program, TIPD LLC and the University of Arizona team established the capability to design, fabricate, and test high-speed, low-loss, hybrid Si/polymer miniature phase modulators with a completely novel Si waveguiding infrastructure design. The key component of the light guiding structure in our hybrid devices is based on a nanoscale Si waveguide design, namely, a Si nanostrip that is an extremely narrow strip waveguide, whose width is down to 100 nm or less. The light guiding infrastructure design has been greatly simplified and the fabrication complexity has been vastly reduced, compared with either the photonic crystal or nanoslotted waveguide approach. Together with our proven capability in EO polymer processing and poling, these developments have allowed for miniaturization, enhanced efficiency, and ease of light coupling for the hybrid EO modulators. An illustration of the design of a hybrid EO polymer/Si nanostrip phase modulator is shown in Figure 1 below.

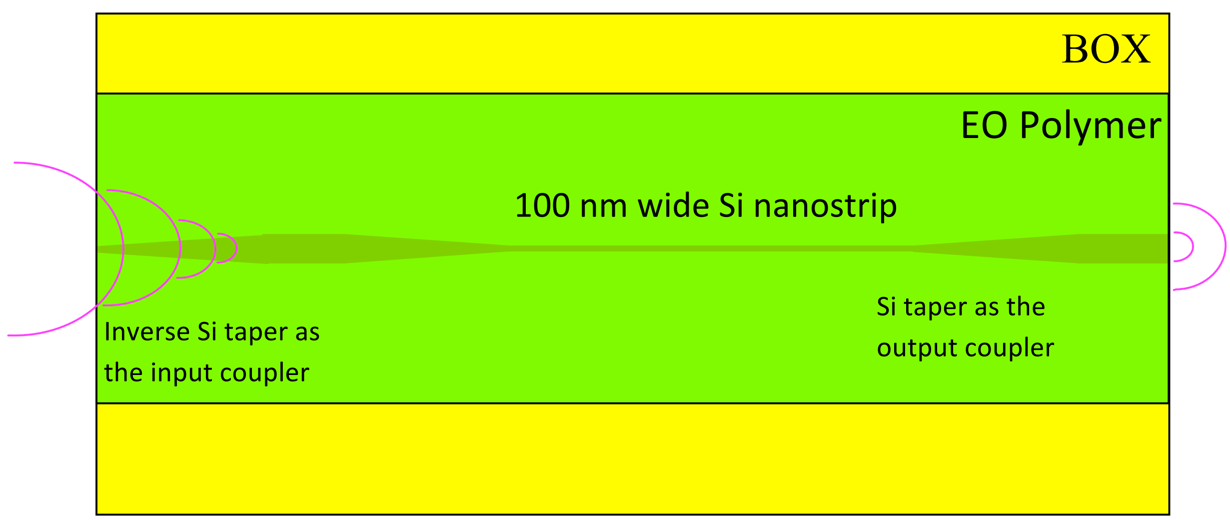


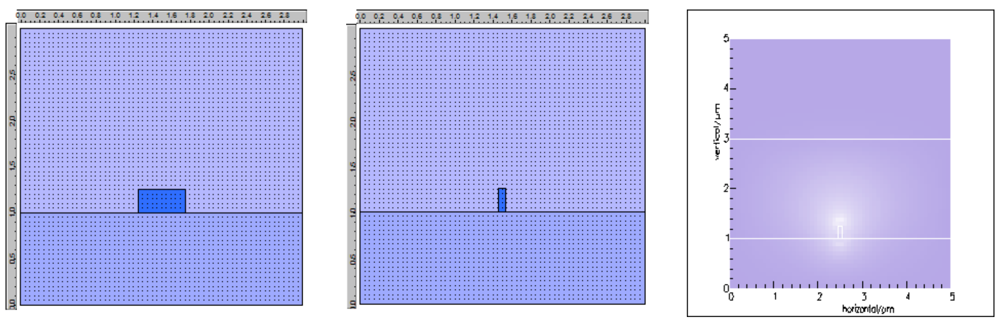
Figure 1. Illustration of a hybrid polymer/Si nanostrip phase modulator

3. CONCEPT, MATERIAL, AND PROCEDURE

3.1 Silicon Nanostrip Concept

The simplest and most common Si waveguide format is a rectangular strip. The condition for single mode operation is to maintain its dimensions at approximately 500 nm wide by 200 nm thick. Due to the large refractive index difference between Si and the surrounding material, the near infrared light at wavelength of 1550 nm is well confined inside the Si strip – resulting in a tight spot deeply buried in the waveguide that is nearly impossible to access by external functional materials such as EO polymers.

There is an elegant and simple approach to cause interaction between the guided light and the functional EO materials, other than the sophisticated nanoslotted waveguide design that will be discussed in detail in Section 4.1.1. It is well known that, if we reduce the width of a strip waveguide below a certain threshold, the light will eventually lose its confinement. In the case of an Si waveguide, the width of the strip needs to be reduced to 100 nm or less – resulting in a so called Si nanostrip. Guided light propagation in Si nanostrips is fundamentally different from that in a conventional strip waveguide. Since the nanostrip width is at least an order of magnitude less than the signal wavelength of 1.55 μm, light cannot be confined inside the Si structure and it largely leaks into the surrounding medium. Such Si nanostrips were initially designed as mode size converters in order to reduce coupling loss to optical fibers [7-9]. For Si nanostrips, light will be mostly present outside of the nanostrips, either on top or below - depending on the refractive indices of the top and bottom cladding media. If on top of the Si nanostrip, we cast a layer of EO polymer whose index is higher than that of the BOX layer (refractive index of ~1.45), the guided light will largely reside within the top EO polymer cladding instead of in the underlying BOX layer. Furthermore, when light propagates along the Si nanostrip, it can be viewed, intuitively, as a trolley riding along the rail - a nanoscale Si "light rail". There will then be no obvious sources of optical transmission loss other than material loss. Figure 2 below shows a regular Si strip waveguide, a Si nanostrip, and its fundamental transverse magnetic (TM) mode. Our simulation shows that as much as 95% of the intensity resides outside of the Si nanostrip for this waveguide.



(a) (b) (c)

Figure 2. (a) Si strip waveguide (500 × 260 nm); (b) Si nanostrip (100 × 260 nm); (c) TM mode of the Si nanostrip with a top polymer cladding (2 µm thick)

Because of the overwhelming presence of the intensity inside the polymer cladding, the EO modulation efficiency achievable for this hybrid device can be as effective as a pure polymer modulator; meanwhile, the coupling-in, transmitting, and coupling-out of the signal light are all accomplished utilizing the Si waveguiding infrastructure - a realistic and promising photonics-on-a chip approach.

3.2 Material Preparation

Electro-optic polymers, primarily SEO100, were obtained from the University of Washington and Soluxra LLC, Kenmore, Washington. SEO100 is a commercially available off-the-shelf product and the material does not need to be further purified. SEO100 is delivered as a dried blend of EO chromophore with the host polymer system and ready to be dissolved in an appropriate solvent. The solvent we used was dibromomethane and the typical concentration was 5.8 wt% for the SEO100 EO polymer solution. EO polymer thin films were spin coated on indium tin oxide (ITO) coated glass slides for standard EO coefficient measurements. After spin coating, a thin gold layer was sputtered through a shadow mask on top of the polymer film to serve as the top electrode layer. The ITO layer was 45 nm thick and the ITO glass slides were supplied by Thin Film Devices; this ITO was chosen to have a low plasma frequency, so as to minimize deleterious reflections that can plague EO coefficient testing. Optimized poling profiles that have been developed in collaboration with the University of Washington were utilized.

3.3 Electro-optic Measurement

We used the Teng-Man ellipsometric measurement technique [10] to determine the r_{33} coefficient of the poled EO polymer films, and we made the measurements at a wavelength of 1310 nm. The detrimental effects caused by ITO absorption and reflection at 1310 nm are far less than that at 1550nm, while the obtained parameters can be reasonably extrapolated to 1550 nm using the two-level model. We measured r_{33} versus poling voltage as well as chromophore concentration so that we could optimize parameters for each process. Excellent agreement between the EO coefficients obtained from the Teng-Man measurements and those derived from actual device performance [11] were consistently observed.

4. RESULTS AND DISCUSSION

4.1 Nanoscale Silicon Waveguide

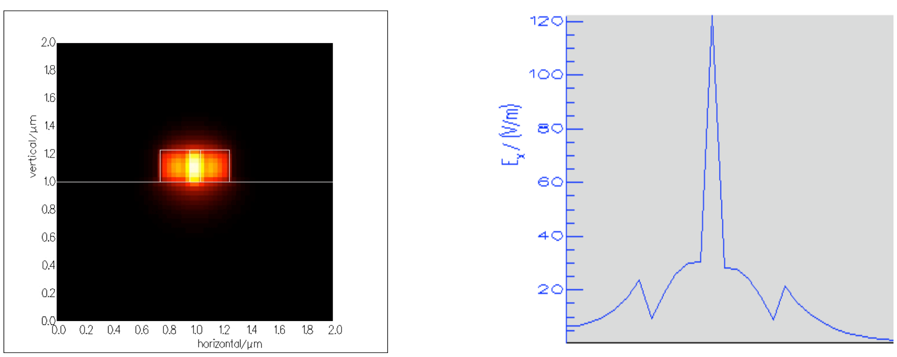
4.1.1 Silicon Nanoslot Fabrication and Test

During the beginning of the project, significant effort was dedicated to the fabrication of Si nanoslots, which were initially designed as the fundamental waveguiding infrastructure. The Si waveguides and nanoslots were fabricated with the E-beam lithography team at the Wright Patterson Air Force Base and the nano-fabrication facility at the University of California, Santa Barbara.

To confine, guide, and control near and mid infrared light in silicon waveguides, we used silicon-on-insulator (SOI) substrates, consisting of a thin (several hundred nanometer) Si layer on top of a buried oxide (BOX) layer of thickness up to a few microns. The BOX layer is further resting on a Si carrier wafer. SOI is widely used in current complementary metal–oxide–semiconductor (CMOS) technology because the BOX layer has low parasitic capacitance and leakage current; for similar reasons, SOI is an outstanding candidate for hosting Si photonic devices such as EO modulators.

Si provides good transparency at optical communication wavelengths, 1.3 –1.6 μm, and has tight confinement of the guided light because of its high refractive index (~3.5). Single-mode silicon strip waveguides typically have dimensions of ~200 nm in height and ~500 nm in width – these nanoscale featured sizes can substantially reduce the size, weight, and power of devices targeted for military hardware systems. However, as previously described, the tightly confined light inside the Si waveguide can only interact weakly with cladeing active EO polymers, which results in very inefficient modulator devices.

It was recently discovered that if a narrow slot, with the width of a few tens to up to 100 nm, is introduced at the center of a Si strip waveguide, a large enhancement of the electric field (as much as 20 times) of the transverse electric (TE) mode can be achieved inside the slot [5]. Figure 3 below presents an example of the TE mode intensity distribution in a typical nanoslotted waveguide: height of 230 nm, overall width of 500 nm and the slot width of 80 nm. In the calculation, the central slot is assumed filled with low-index (1.5) dielectric material. The polarization of the TE mode is along the horizontal orientation. Nanoslotted waveguides can greatly enhance the electro-optic interaction if the nanoslot is filled with EO polymers [12] for ultrafast modulation.



(a) (b)

Figure 3. (a) TE mode of a Si nanoslot; (b) modal intensity profile

Based on the polymer-infiltrated Si nanoslot modulator device concept, Si nanoslots were designed and fabricated during the early part of the program. Figure 4 below shows samples of fabricated nanoslotted Si waveguides on SOI wafers. Figure 4 presents a nanoslotted waveguide that is 260 nm high, 500 nm wide overall with a central slot of 148 nm in width.

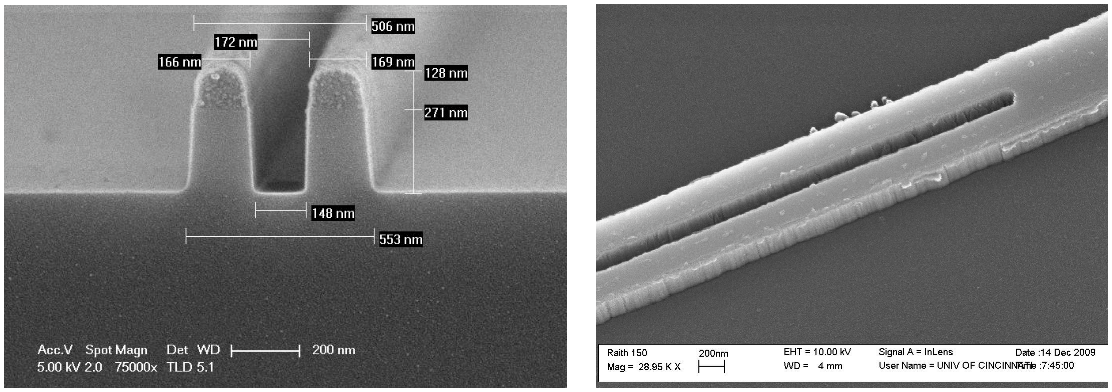


Figure 4. SEM Photos of Fabricated Si Nanoslotted Waveguides

Si nanoslotted waveguides of slot width ranging from 50 to 150 nm were fabricated and tested for transmission properties. Near infrared light at 1310 nm was launched using a tapered fiber coupler that had a mode field diameter of 2.5 μm. Figure 5 below shows the transmitted light through a 50-nm wide nanoslotted waveguide.

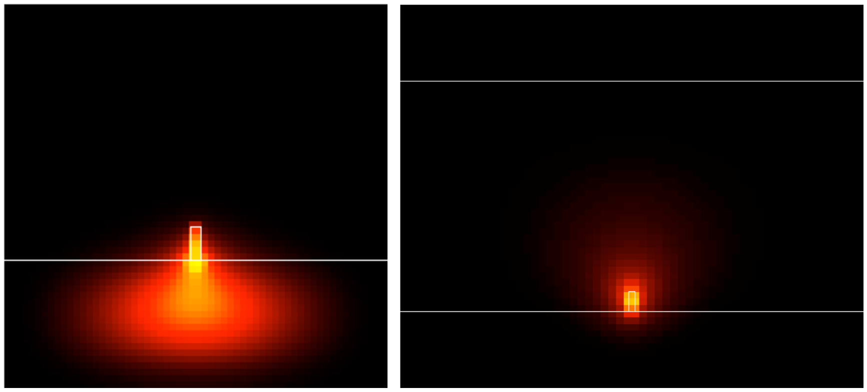
Figure 5. Transmitted light through a 50-nm wide nanoslotted waveguide

Although the light was successfully transmitted through Si nanoslotted waveguides, substantial transmission loss was also observed. For a 3-mm long, 50-nm wide nanoslotted waveguide, ~40 dB overall transmission loss was observed. This loss number would be very hard to overcome because the mode mismatch between the tapered fiber mode and the nanoslotted waveguide mode is inevitable. Furthermore, the extreme challenge of depositing electrodes on both walls of the nanoslotted waveguide further complicates this device approach.

4.1.2 Silicon Nanostrip Fabrication and Test

In order to build a realistic and efficient Si/polymer hybrid modulator device, an innovative and alternative Si infrastructure was explored in the latter part of this program. This new light guiding infrastructure utilized a geometry complementary to that of the nanoslotted waveguide, namely, a nanostrip, the width of which ranged from 50 to 100 nm.

The Si nanostrips were made on the same SOI wafers that were used for nanoslot fabrication. To effectively guide light and provide EO modulation, a planarizing polymer cladding layer should be cast on top of the Si nanostrip. The top EO polymer cladding not only provides the modulation functionality, but also helps to define the fundamental TM mode of the Si nanostrip. Without the top polymer cladding, the TM mode of the Si nanostrip exposed in air will leak substantially into the BOX layer, as shown in Figure 6(a); with a top polymer cladding whose refractive index is larger than that of the BOX layer, the TM mode will be present inside the polymer, as shown in Figure 6(b). The thickness of the top polymer layer is set to be 2.0 μm. It is to be noted that the Si nanostrip does not support a fundamental TE mode with a flat top cladding. In order to support fundamental TE mode operation, an external polymer channel waveguide has to be introduced, which will be discussed in Section 4.3.



(a) (b)

Figure. 6. TM modes of a Si nanostrip in air (a) and with a top polymer cladding (b)

Si nanostrips were subsequently fabricated at Wright Patterson Air Force Base and the nano-fabrication facility at the University of California, Santa Barbara. Figure 7 shows an SEM photo of a fabricated Si nanostrip on SOI substrate that is 92 nm wide and 260 nm high.

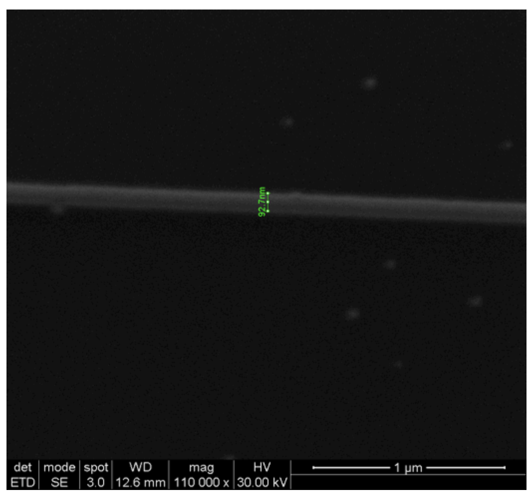


Figure 7. Fabricated Si Nanostrip on SOI Substrate

To test the transmission performance of the fabricated Si nanostrips, a flat layer of poly (methyl methacrylate) (PMMA) was spin coated on top of the nanostrips. The PMMA layer had a thickness of about 2 µm. Without the top PMMA cladding, light could not be transmitted through the Si nanostrips, despite repeated attempts. Launched by a tapered fiber coupler, near infrared light transmission was observed with only modest coupling effort. Figure 8 shows 1310 nm light transmitted through the PMMA-covered 50-nm wide Si nanostrip.

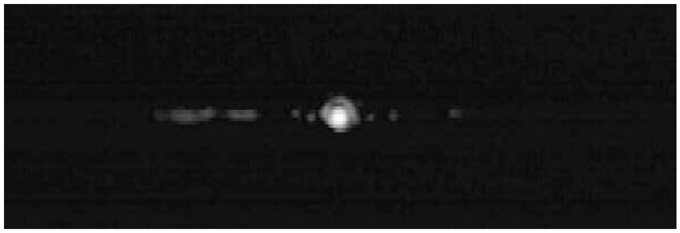


Figure 8. Light transmitted through a 50-nm wide Si nanoslot

4.2. Material Selection

Both TIPD LLC and the University of Arizona have significant experience with state-of-the-art EO polymers. A series of breakthrough publications have been reported over the past few years [11, 13-15]. The key figure-of-merit for EO polymers in devices is $n_{eff}^3 r_{eff}/\alpha$, where n_{eff} is the effective refractive index of the mode, r_{eff} is the in-device EO coefficient (usually equivalent to r_{33}), and α is the optical loss of the active region of the device. Through years of study, we have concluded that to obtain the device figure-of-merit, it is crucial to understand its dependence upon the actual device configuration. Therefore, we have adopted the following criteria for the EO chromophores and polymers selection regarding the current project:

1. High EO coefficient in hybrid devices (> 60 pm/V);
2. Low optical loss at 1550 nm (~ 2 dB/cm);
3. EO chromophore availability in quantities of a few hundred milligrams;

Based on these criteria we selected the commercially available chromophore/polymer SEO100 as the Phase II benchmark EO material. The SEO100 was obtained from Soluxra LLC, Kenmore, Washington, and it has been comprehensively investigated in multiple projects at TIPD, LLC and the University of Arizona. The chromophore system of SEO100 is suitable as it has the combined benefits of high r_{33}, low optical loss, excellent processability and stability, as well as commercial accessibility.

4.3 Phase Modulator Fabrication and Test

As we stated in Section 4.1.2, with a flat top cladding, Si nanostrips can only operate in the fundamental TM mode, which presents challenges for the electrode design. If we further confine the EO polymer cladding to achieve a channel waveguide, as shown in Figure 9, the Si nanostrip inside can support both TE and TM modes with the external modal confinement given by the channel waveguide. In supporting both TE and TM modes, the polymer channel waveguide and Si nanostrip waveguide combination provides the flexibility to selectively operate in either mode, whichever is compatible with other Si photonic devices that are present on the same chip.

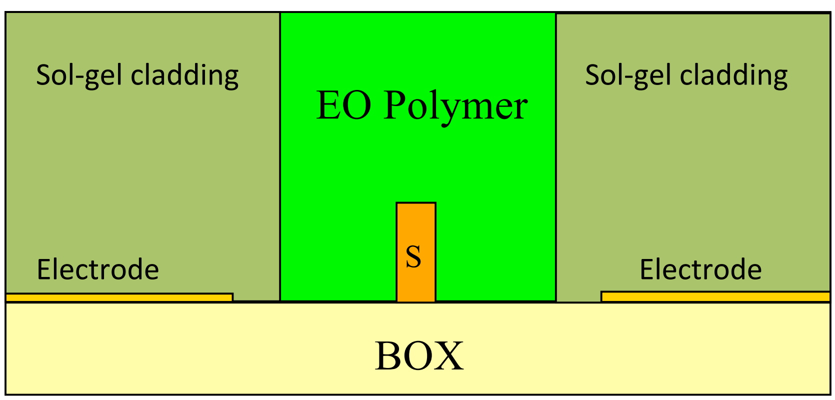


Figure 9. Cross-section of the active polymer/Si nanostrip region

Figure 9 illustrates the detailed design of the cross-section of the active polymer/Si nanostrip modulation region. In this design, a flat sol-gel layer is first cast on top of the Si nanostrips. Next, a trench is etched to remove the sol-gel that covers the nanostrip. Then, EO polymer is filled into the trench and covers the nanostrip. The fundamental TE mode is the selected mode to operate in this design and, correspondingly, the electrodes are deposited directly on the BOX layer and covered by the sol-gel cladding. An additional benefit of the channel waveguide format is that it can prevent the signal light from penetrating to where the electrodes are, and thus reduces the electrode-induced attenuation to a minimum. In our design, the dimensions of the polymer channel waveguide are 3 × 3 µm.

Figure 10 below shows the fabricated Si nanostrip (the visibly faint central line) and the electrodes that are deposited directly on the SOI substrate. The sol-gel cladding and the EO polymer channel waveguide have not yet been deposited on the substrate in Figure 10.

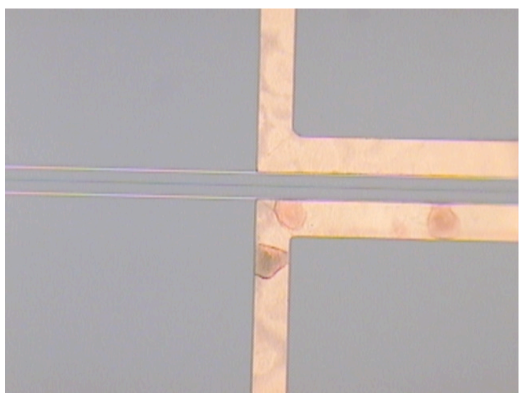


Figure 10. Fabricated Si nanostrip and the deposited electrodes

The standard setup to test phase modulators is shown in Figure 11 below. The device under test, e.g., a polymer/Si nanostrip modulator, is placed between a pair of linear polarizers and a phase compensator. By adjusting the compensator, the phase change of the input light can be thoroughly investigated.

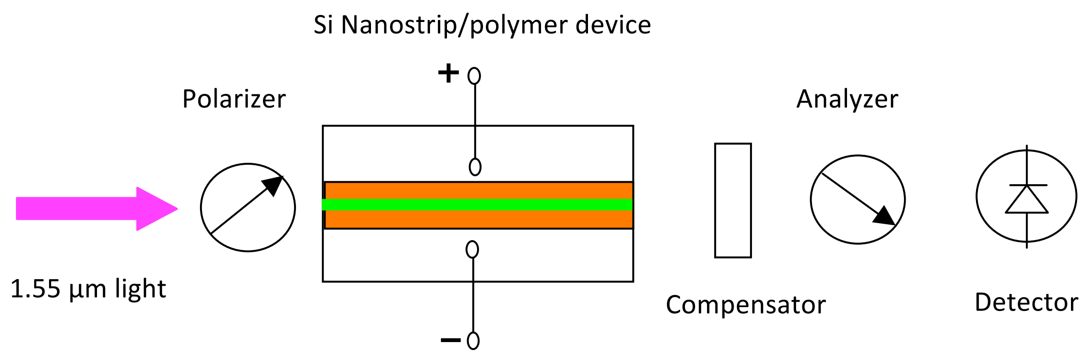


Figure 11. Illustration of the Standard Phase Modulator Test Setup

Hybrid EO modulators were fabricated based on the design principle of the Si nanostrip and the EO polymer channel waveguide [16]. In the completed phase modulator devices, the total device length was 1.4 cm and the active length, i.e., the length of the polymer-covered Si nanostrip, is 3 mm. The separation between the electrode pair is 10 μm and the electrode length is 5.5 mm. By launching 1550 nm light with a tapered fiber coupler, EO modulation was achieved. Figure 12 shows a snapshot of the oscilloscope screen displaying the modulated signal at 1 kHz.

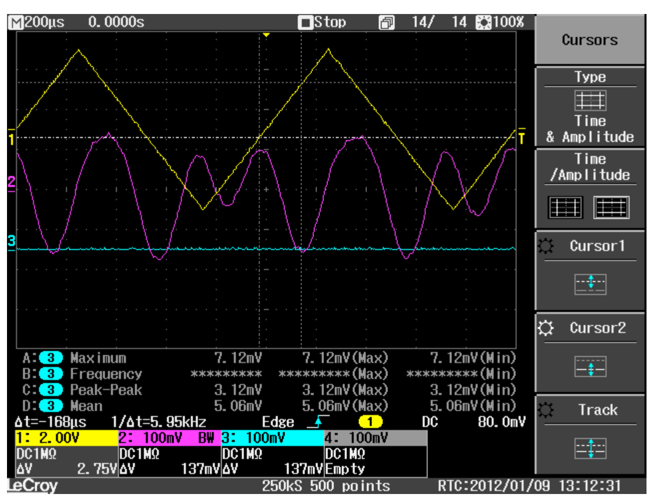


Figure 12. Oscilloscope screen displaying the modulated signal

Regarding the performance of this first ever, proof-of-concept, miniature hybrid polymer/Si nanostrip phase modulator, the measured V_π was 137 V that resulted in an estimated r_{33} of ~10 pm/V in the device. The overall loss of the modulator device (fiber-to-fiber) was ~30 dB. Although the specifications of these primitive miniature phase modulators are still far from ideal, the significance of the realization of the first hybrid, Si nanostrip based, polymer modulator device should not be overlooked. The phase modulators under test here were completed in the final months of the project - the fabrication and engineering of these devices were far from being optimized. With optimal design parameters, tailored fabrication techniques and processing, we firmly believe that significant, orders of magnitude, enhancement of the device performance will be achieved. We note that in our previous highly successful EO polymer/sol-gel hybrid platform, the modulator performance improved from a V_π of 70V at program outset, to < 1 V for current generation devices.

5. KEY PERSONNEL

The key personnel at TIPD, LLC are Dr. Li Li, Dr. Jiafu Wang, and Valery Temyanko. The key personnel at the University of Arizona are Roland Himmelhuber, Adam Jones, Oscar Dario Herrera, Dr. Robert A. Norwood, and Dr. Nasser Peyghambarian.

6. PUBLICATIONS

- Himmelhuber R., Li L., Jones A. M., Herrera O., Norwood R. A., and Peyghambarian N., "An Electro-Optic Silicon-Polymer Hybrid Modulator," No. 8113-04, *SPIE Optics + Photonics*, San Diego, CA, 21–25 August, 2011.

Papers based upon the research results achieved in the final months of this program are in preparation and will include acknowledgement of AFOSR STTR support.

7. CONCLUSIONS

Through this Phase II program, TIPD LLC and the University of Arizona have successfully designed, fabricated, and tested proof-of-concept miniature EO modulators at 1550 nm based on novel Si nanoscale waveguides. We have demonstrated, for the first time to the best of knowledge, miniature hybrid EO modulators built on SOI substrates combining Si nanostrip waveguides and high performance EO polymers. The accomplishment of the hybrid SOI-based polymer modulators presented in the body of this report will serve as a solid foundation for achieving the eventual goal of simultaneous electronic and photonic functions on the same silicon chip.

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